RESEARCH DEPARTMENT

A theoretical study of the application of electronic masking to television

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A THEORETICAL STUDY OF THE APPLICATION OF ELECTRONIC MASKING TO TELEVISION

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A THEORETICAL STUDY OF THE APPLICATION OF ELECTRONIC MASKING TO TELEVISION

SUMMARY

Electronic masking enables a film scanner to be used to recover, from the film, information relating to its original exposure to the scene. This report considers how this may best be done, having regard to requirements for colorimetric accuracy and good noise performance. The suitability of the original exposure to the television display is then examined, and proposals for film analysis correction are made. The complete process envisaged would enable the closest match possible to be made between pictures obtained from television cameras and film scanners.

1. INTRODUCTION

When designing a colour television film scanner it has been customary up to the present to aim to reproduce the film as it would have appeared had it been optically projected. Correction may be made for certain errors caused by faulty processing[1], but otherwise discrepancies between colours in the original scene and their reproduction by the positive print are ignored; it is assumed that the colours observed when the film is optically projected are those which the producer intended the viewer to see. Moreover it is possible to design the scanner analysis so as to achieve a very close equivalence to optical projection[2].

The pleasing appearance of pictures obtained by optical projection is evidenced by the widespread popularity of colour film, but if a close comparison with the original scene is made, substantial colour errors are found to be present. These errors may sometimes be deliberately introduced to create special artistic effects, but are generally not desired.

A colour reproduction process such as colour television in which the light from three primary sources is combined additively can in theory be designed to reproduce the original scene with complete accuracy subject to the colour gamut of the primaries used*. Such precision cannot be achieved however when a subtractive process such as colour film is used. In fact the mode by which colour is synthesized by the selective transmission of light through the three dyes used in a film transparency renders an exact reproduction of all colours impossible.

The chief imperfection of colour film is that each dye has an absorption in spectral regions where absorption is undesirable. These unwanted absorptions cause the reproduced colour to suffer a change in chromaticity together with a loss of luminance. The effect may be partially compensated by raising the gamma of the photographic process, by the incorporation of photographic masking, and by modifying the taking sensitivities so that they no longer approximate to the colour-mixture curves suggested by certain theoretical considerations (see Section 2.4).

Although these techniques are used, however, the colour accuracy of a photographic process from camera to optical projection is considerably less than that attainable by a television system.

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* For complete accuracy within the gamut of the primaries the colour analysis should be made according to 'colour mixture curves', obtained by appropriately combining the CIE distribution functions $\bar{x}$, $\bar{y}$ and $\bar{z}$. Moreover a $[3 \times 3]$ linear matrix enables the colour-mixture curves appropriate to any one set of primaries to be made appropriate to any other set.

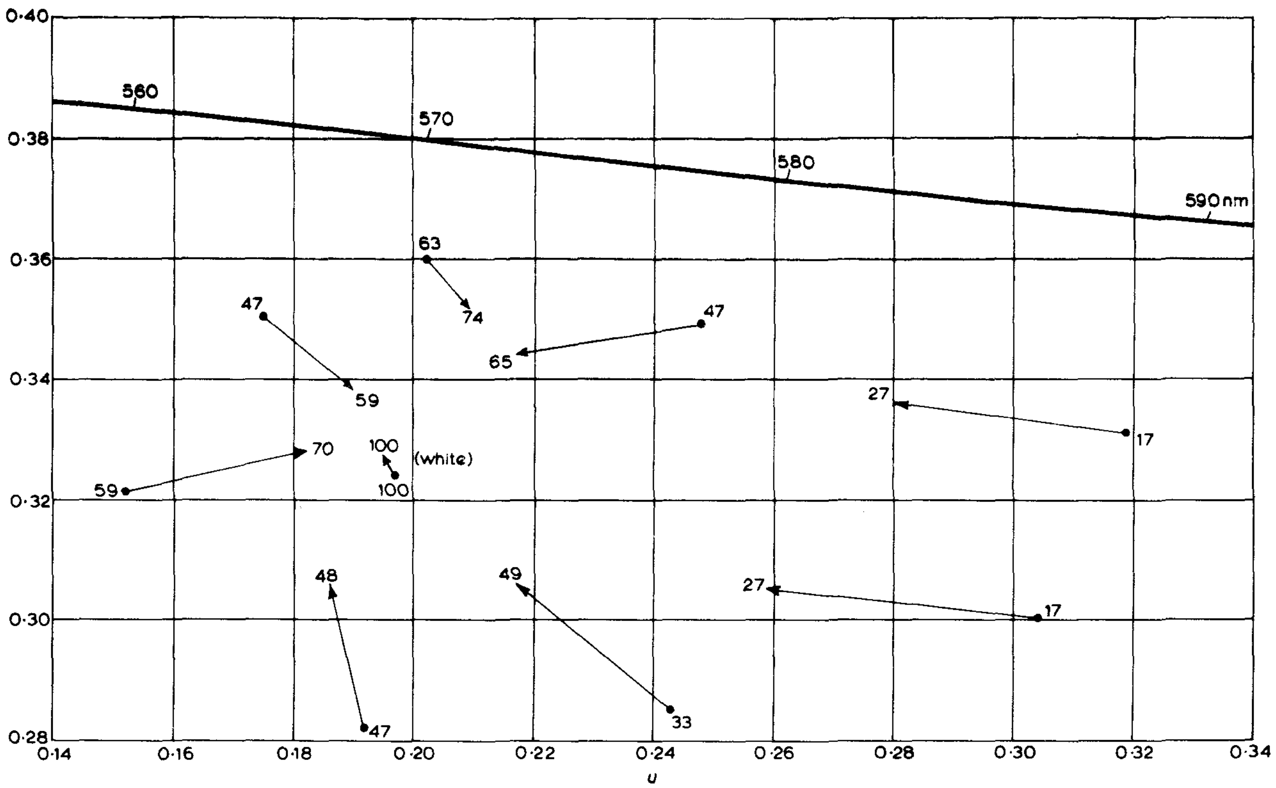

Fig. 1 - Measured reproduction of a number of test colours by a typical film process Figures are relative luminances expressed as percentages of that of white. Reproduced colours at arrow heads.

Fig. 1 shows the measured reproduction by a typical colour film of a series of test colours. The projector used in making these measurements had its white point set not quite to that specified for colour television (Illuminant C), but the errors of reproduction shown would not be much affected if the small adjustment of white point to Illuminant C were made.

Fig. 2 shows the result of a calculation in which the same colours * were supposed to be analysed by a 3-tube colour television camera incorporating a linear matrix[2]. These errors are much smaller.

It is therefore apparent that unless the colour errors introduced in the photographic process are compensated when the film is televised, the resulting pictures will be inferior to those obtained using a television camera. The discrepancy will be most marked when colour film is used to provide inserts into live programmes.

It has for some time been realized that by suitably processing ('electronic masking') the three signals produced by a colour telecine machine it is possible to offset some of the degradations inherent in the photographic process and thus to obtain an approximation to the colours in the original scene which is closer than that obtained by projection of the positive print. Although the principles were laid down by Burr in 1954[3], the electronic techniques then available did not permit more than an approximation to electronic masking. More recently, it has been demonstrated by Wood and Griffiths[4] that a more complete realization of the principle is practicable and can lead to a useful improvement in the colour picture.

The present work was undertaken to determine the best optical analysis for use in a colour telecine machine when it is intended to make use of electronic masking. The use of an additional correction for the original film taking sensitivities is also examined.

2. BASIC PRINCIPLES

2.1. Electronic Masking

The basic concept underlying the electronic masking technique is that the positive print supplied to the telecine machine may be regarded not merely as a device for synthesizing colour, but as three distinct photographic recordings of colorimetric measurements of the original scene made when the

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* The small discrepancies between the original colours plotted in Figs. 1 and 2 are due to measurement errors.

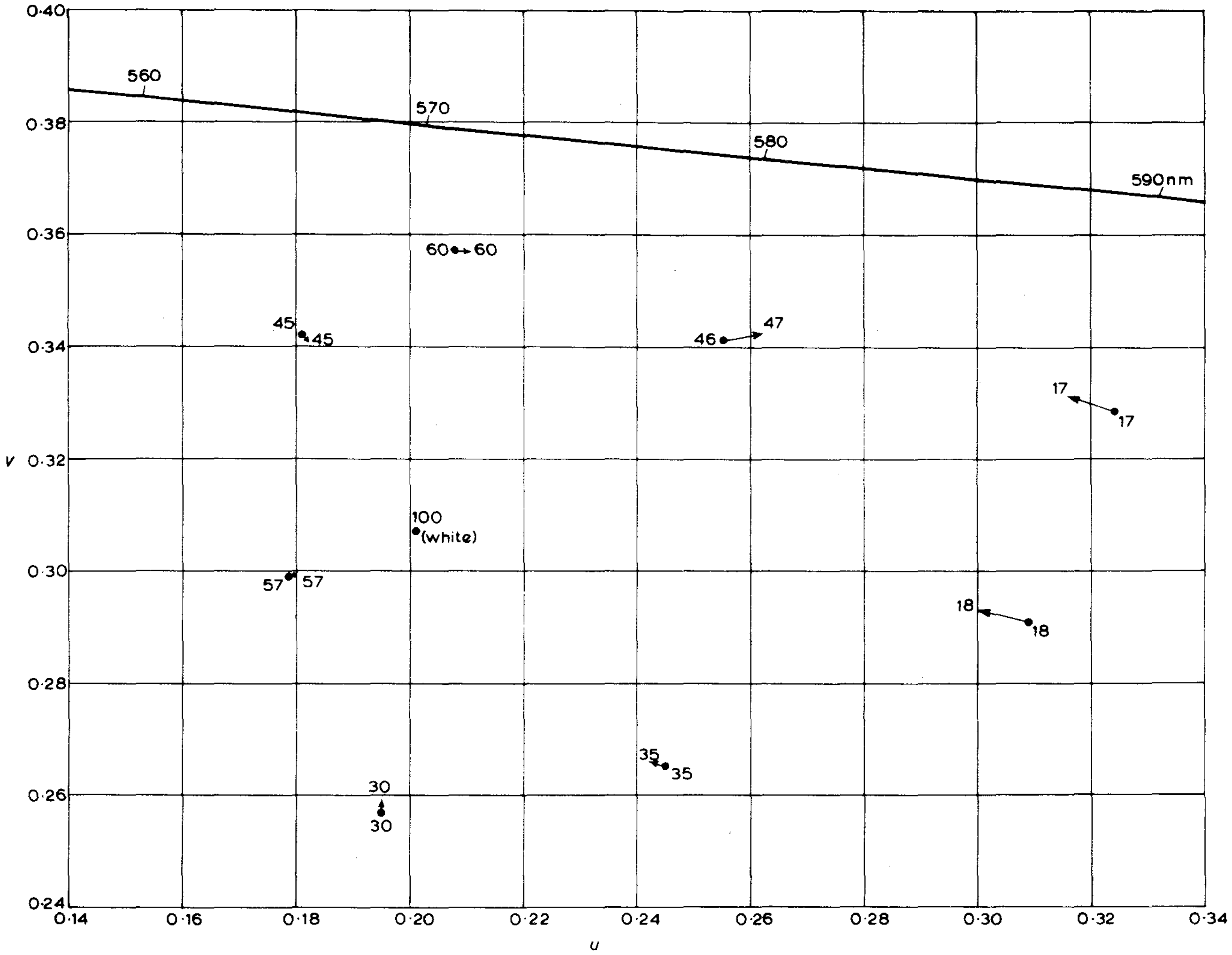

Fig. 2 - Calculated reproduction of a number of test colours by a three-tube colour television camera adjusted to have optimum analysis characteristics, the display using NTSC primaries
Figures are relative luminances, expressed as percentages of that of white
Reproduced colours at arrow heads

film was first exposed. The mechanism by which the information recorded on the film during its initial exposure to the scene is relayed to the telecine machine will now be described. Fig. 3(*a*) summarizes the main steps involved.

The original photographic emulsion on the negative contains three layers, one red-, one green-, and one blue-sensitive. Thus three separate exposures are simultaneously made, whose magnitudes are given by

$$R_0 = \int V(\lambda)\ S_r(\lambda) d\lambda$$

$V(\lambda)$ being the spectral energy distribution of the incident light, and $S_r(\lambda)$ the sensitivity distribution of the red emulsion, and similarly

$$G_0 = \int V(\lambda)\ S_g(\lambda) d\lambda$$

$$B_0 = \int V(\lambda)\ S_b(\lambda) d\lambda$$

It is these exposure levels that subsequently control the concentrations of the three dyes forming the final print.

Thus if the film scanner is employed not for conventional colour analysis but as a densitometer designed to measure the densities of the three colour-print dye layers, the appropriate signal processing then enables voltages proportional to R_0, G_0 and B_0 to be obtained. The accuracy with which colours may then be reproduced on the television display depends not on the limitations of the dye characteristics but on the extent to which the original taking sensitivities $S_r(\lambda)$, $S_g(\lambda)$ and $S_b(\lambda)$ depart from colour mixture curves. The suitability of the film taking sensitivities will be further discussed in Section 2.4.

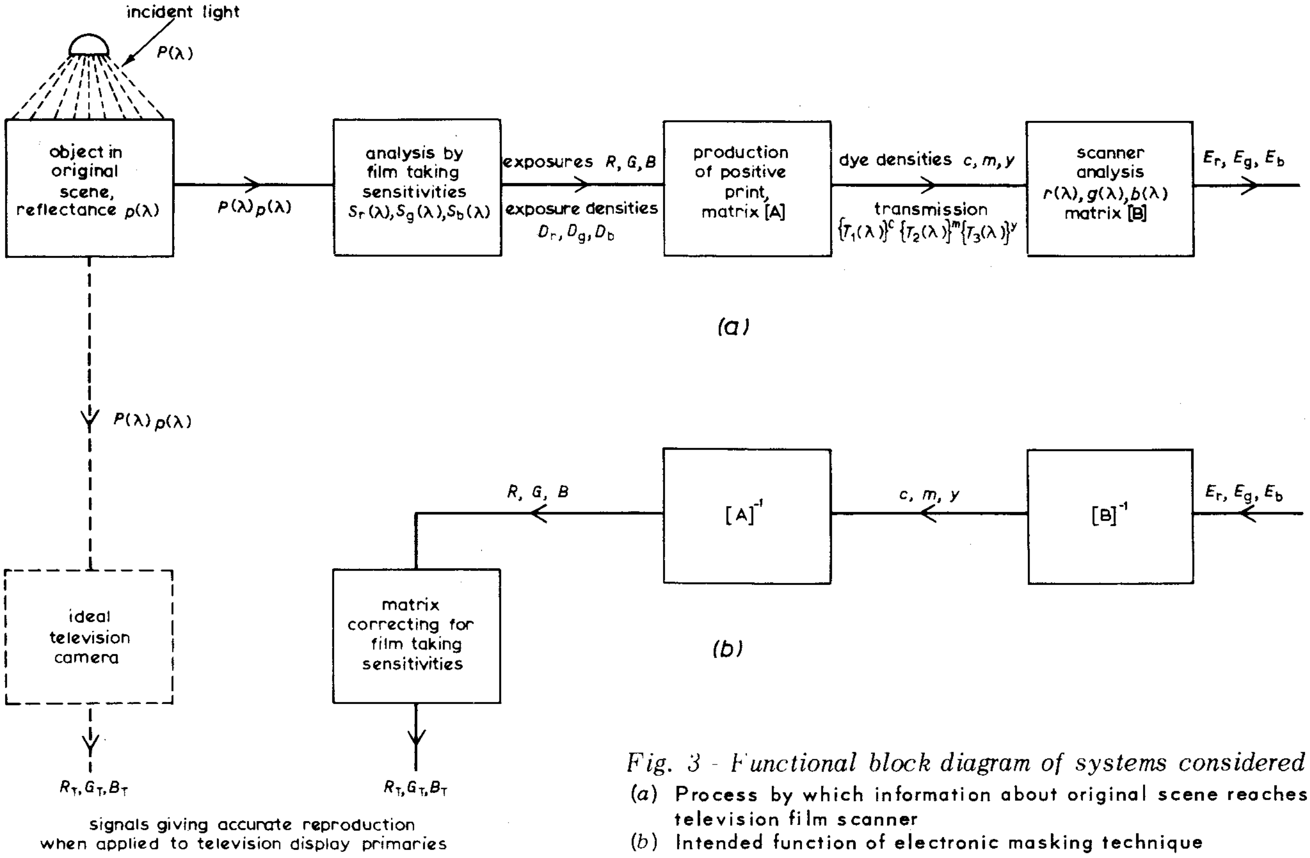
incident light
$P(\lambda)$
object in original scene, reflectance $p(\lambda)$
$P(\lambda)p(\lambda)$
analysis by film taking sensitivities $S_r(\lambda), S_g(\lambda), S_b(\lambda)$
exposures R, G, B
exposure densities D_r, D_g, D_b
production of positive print, matrix [A]
dye densities c, m, y
transmission $\{T_1(\lambda)\}^c \{T_2(\lambda)\}^m \{T_3(\lambda)\}^y$
scanner analysis $r(\lambda), g(\lambda), b(\lambda)$ matrix [B]
E_r, E_g, E_b
(a)
$P(\lambda)p(\lambda)$
ideal television camera
R_T, G_T, B_T
signals giving accurate reproduction when applied to television display primaries
R, G, B
$[A]^{-1}$
c, m, y
$[B]^{-1}$
E_r, E_g, E_b
matrix correcting for film taking sensitivities
R_T, G_T, B_T
(b)

Fig. 3 - Functional block diagram of systems considered
(*a*) Process by which information about original scene reaches television film scanner
(*b*) Intended function of electronic masking technique

2.2. Development of Masking Equation

It is convenient to deal not with absolute values of exposure but with values expressed relative to those corresponding to a perfectly reflecting white in the scene. Thus if $V(\lambda) = P(\lambda) \cdot p(\lambda)$ where $P(\lambda)$ is the spectral energy distribution of the illuminant and $p(\lambda)$ is the spectral reflectance (or transmittance) of a given object, the relative exposures R, G and B forming the latent images on the negative emulsion are obtained as

$$R = \frac{\int S_r(\lambda)P(\lambda)p(\lambda)\mathrm{d}\lambda}{\int S_r(\lambda)P(\lambda)\mathrm{d}\lambda}$$

etc.

The logarithms (to base 10) of the reciprocals of these quantities are known as exposure densities D_r, D_g, D_b, i.e.

$$D_r = -\log_{10} R \;\ldots\ldots \qquad (1)$$

etc.

Exposure densities are convenient quantities to use because if the subsequent film process were entirely linear and if the red, green and blue exposures were made to influence the concentrations of only the cyan, magenta and yellow dyes respectively in the final print, these positive print dye densities* c, m and y would be proportional respectively to D_r, D_g and D_b. The constant of proportionality would represent the gamma of the system.

Dye densities are expressed in terms of 'equivalent neutral density' (e.n.d.) units. An e.n.d. of 1 is the normalized density of a given dye necessary in combination with the appropriate amounts of the other two dyes to produce a neutral of density 1 (transmission 10%) when viewed using a given illuminant.

In practice, each of the three dye densities is influenced by all three exposures. It is therefore more accurate to say that

$$\begin{bmatrix} c \\ m \\ y \end{bmatrix} = \begin{bmatrix} \\ \mathrm{A} \\ \\ \end{bmatrix} \begin{bmatrix} D_r \\ D_g \\ D_b \end{bmatrix}$$

---

* To achieve a reasonable contrast characteristic within the working range, it is usual to arrange that 'white' is represented on the print by a neutral of density about 0·3. This neutral is effectively superimposed upon all film colours, and it will therefore be ignored in this description, although when making calculations it should be taken into account.

where [A] is a [3 x 3] matrix. This cross-coupling, if unintentional**, is referred to as 'interimaging' but to improve colour rendering a controlled degree of crosstalk may be deliberately introduced between exposure and final print by means of photographic masking.

Even the above representation is only approximate because interimaging is in fact a non-linear process; moreover the characteristic curves of the emulsions, expressing density as a function of the logarithms of the exposure, are non-linear. Nevertheless a reasonable approximation results from assuming that a linear relationship exists between the original exposure densities and the final dye densities, particularly if the above equation is made to hold good at densities around mid-grey.

If the cyan, magenta and yellow dye layers in the positive print have spectral transmittances $T_1(\lambda)$, $T_2(\lambda)$ and $T_3(\lambda)$ that correspond to an e.n.d. of unity, the spectral transmission of the positive print (ignoring the base) corresponding to a colour requiring (normalized) dye densities c, m and y is given by the product of the spectral transmissions of the individual layers; it is

$$[T_1(\lambda)]^c \,.\, [T_2(\lambda)]^m \,.\, [T_3(\lambda)]^y$$

Hence, if the scanner has normalized analysis characteristics (including the cathode-ray tube, photo-multiplier and optical elements) given by $r(\lambda)$, $g(\lambda)$ and $b(\lambda)$, the signal voltages obtained from the scanner are

$$\begin{aligned} E_r &= \int r(\lambda)\,[T_1(\lambda)]^c \,.\, [T_2(\lambda)]^m \,.\, [T_3(\lambda)]^y \, d\lambda \\ E_g &= \int g(\lambda)\,[T_1(\lambda)]^c \,.\, [T_2(\lambda)]^m \,.\, [T_3(\lambda)]^y \, d\lambda \qquad (2) \\ E_b &= \int b(\lambda)\,[T_1(\lambda)]^c \,.\, [T_2(\lambda)]^m \,.\, [T_3(\lambda)]^y \, d\lambda \end{aligned}$$

(ignoring a normalizing constant)

Suppose now that $r(\lambda)$ is zero except for $(\lambda_r - \tfrac{1}{2}\delta\lambda) < \lambda < (\lambda_r + \tfrac{1}{2}\delta\lambda)$ where $\delta\lambda$ is vanishingly small, and that $\int r(\lambda)\, d\lambda = 1$, i.e. that the red analysis is by means of monochromatic light.

Then equation (2) becomes

$$E_r = [T_1(\lambda_r)]^c \,.\, [T_2(\lambda_r)]^m \,.\, [T_3(\lambda_r)]^y \tag{3}$$

etc.

so that

$$\log E_r = c \log T_1(\lambda_r) + m \log T_2(\lambda_r) + y \log T_3(\lambda_r) \tag{4}$$

similarly for E_g and E_b with $\lambda = \lambda_g$ and $\lambda = \lambda_b$ respectively.

Now $\log T_1(\lambda_r)$ etc. are constants depending on the dye density characteristics. Therefore

$$\begin{bmatrix} \log E_r \\ \log E_g \\ \log E_b \end{bmatrix} = \begin{bmatrix} \\ \mathrm{B} \\ \\ \end{bmatrix} \begin{bmatrix} c \\ m \\ y \end{bmatrix} \tag{5}$$

$$= \begin{bmatrix} \\ \mathrm{B} \\ \\ \end{bmatrix} \begin{bmatrix} \\ \mathrm{A} \\ \\ \end{bmatrix} \begin{bmatrix} D_r \\ D_g \\ D_b \end{bmatrix}$$

$$= \begin{bmatrix} \\ \mathrm{B} \\ \\ \end{bmatrix} \begin{bmatrix} \\ \mathrm{A} \\ \\ \end{bmatrix} \begin{bmatrix} -\log R \\ -\log G \\ -\log B \end{bmatrix}$$

where [B] is another (3 × 3) matrix

hence

$$\begin{bmatrix} \log R \\ \log G \\ \log B \end{bmatrix} = \begin{bmatrix} \\ \mathrm{C} \\ \\ \end{bmatrix} \begin{bmatrix} \log E_r \\ \log E_g \\ \log E_b \end{bmatrix} \tag{6}$$

$$\begin{aligned} \text{where } [\mathrm{C}] &= -\{[\mathrm{B}]\,[\mathrm{A}]\}^{-1} \\ &= -[\mathrm{A}]^{-1}\,[\mathrm{B}]^{-1} \end{aligned} \tag{7}$$

Equation (6) indicates that, in so far as the above analysis is an accurate representation of the film process, it is possible to operate upon the signals produced by the telecine machine to recover the information obtained when the film was originally exposed. This operation, performed by the electronic masking unit, effectively retraces the steps involved in the film-telecine process, as Fig. 3(*b*) indicates. Signals approximately representing the original film exposures are derived by applying the signals obtained at the outputs of the scanner head amplifiers to circuits having a logarithmic characteristic followed by a matrix unit and then circuits having an exponential characteristic. As Equation (7) suggests, the matrix unit may be divided into two parts, the first of which, $[\mathrm{B}]^{-1}$, obtains signals proportional to the dye densities whilst the second, $[\mathrm{A}]^{-1}$, converts these to signals proportional to the original exposure densities.

2.3. Practical Limitations

In present day flying-spot colour scanners the source of light is a cathode-ray tube having a zinc oxide phosphor. The intensity of this source is limited, particularly in the blue and red spectral regions. Thus fairly broad analysis characteristics

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** 'Interimage effects occur in most color photographic processes, but they are not, in general, subject to direct quantitative control, although they can normally be modified advantageously' - Ref. 5, p. 543.

are necessary if a good signal-to-noise ratio is to be achieved. However, the elements of matrix [B] can be fixed quantities only if the analysis of each colour channel is monochromatic. This is because if broad analysis characteristics are used, the integrations defined by Equations (2) are no longer capable of an exact simplification, and it is no longer possible to obtain a simple solution in the form of Equations (4). Therefore the relationship expressed by Equations (4) and (5) can no longer be exact for all colours. The errors resulting from their continued use increase gradually as the analysis is broadened, whilst there is a gradual improvement in the noise performance. Clearly some compromise is called for, in which the visibility of the noise, taken together with that of the colour errors, averaged over the whole gamut of colours (assuming that no one colour is very badly reproduced), is made as low as possible.

This compromise is not easy to reach, since it depends on the basic noise performance of the particular scanner considered, on the necessity for further correction circuits (see Section 2.4), and on the assumed relative importance of colour errors and noise. The calculations described in Section 3.1 were based on certain assumptions relating to the Research Department colour scanner. For optimum results they should be repeated for each type of scanner considered; none the less if an approximately correct analysis is available it is thought sufficient merely to calculate an optimum matrix for the masking unit.

2.4. Suitability of Original Analysis

The original colorimetric analysis of the scene is determined by the taking sensitivities of the three original film emulsions; these have been designed to work with the print dyes in a subtractive colour synthesis.

There does not exist, even in thoery, a unique set of film taking sensitivities that will match the dye absorption (spectral density) characteristics throughout the gamut of colour normally encountered. By various methods[6] a set of colour-mixture curves corresponding to an approximately equivalent set of additive primaries may be found, and these, together with the appropriate photographic masking, would give minimum colorimetric errors. In the context of practical limitations, however, it becomes desirable to depart from such colour-mixture curves, choosing instead relatively narrow sensitivity characteristics having more widely separated peaks.

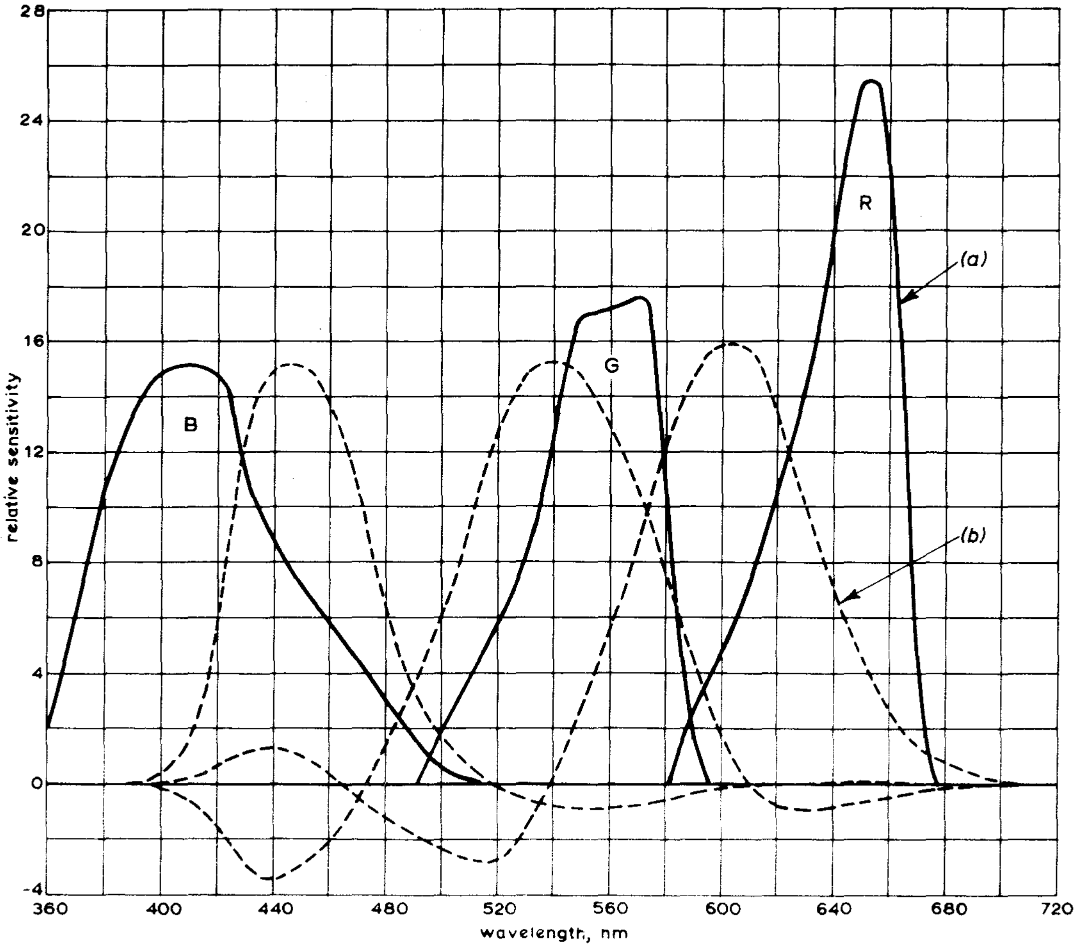

Fig. 4 - Comparison of analysis characteristics of colour film and colour television
(*a*) Taking sensitivities of typical film stock (*b*) Analysis ideally suited to NTSC primaries

When electronic masking is used, however, these original taking sensitivities become the analysis characteristics of the complete film-plus-television system.

Fig. 4 shows at (*a*) and (*b*) respectively a typical set of taking sensitivities, together with the characteristics ideally suited to the NTSC display primaries*.

If characteristics such as those shown at (*a*) are used with NTSC primaries, substantial colour errors are produced. Although the curves depart considerably from colour-mixture curves, and are therefore basically unsuitable for any set of additive primaries, their compatability to the NTSC primaries can be improved by the use of a linear matrix. Section 3.2 describes the calculation of an optimum linear matrix for use with the analysis characteristics shown in curve (*a*) of Fig. 4. Ideally, this matrix should be introduced into the scanner circuit after the masking unit at a point where the colour signals are made to have magnitudes proportional to the original exposures; it should therefore follow circuits having an exponential characteristic (see Fig. 5(*a*)).

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* An illuminant of colour temperature 3200°K is often used when the film is exposed. Analysis curves (*a*) and (*b*), however, are shown in Fig. 4 normalized with respect to Illuminant C so that they may readily be compared.

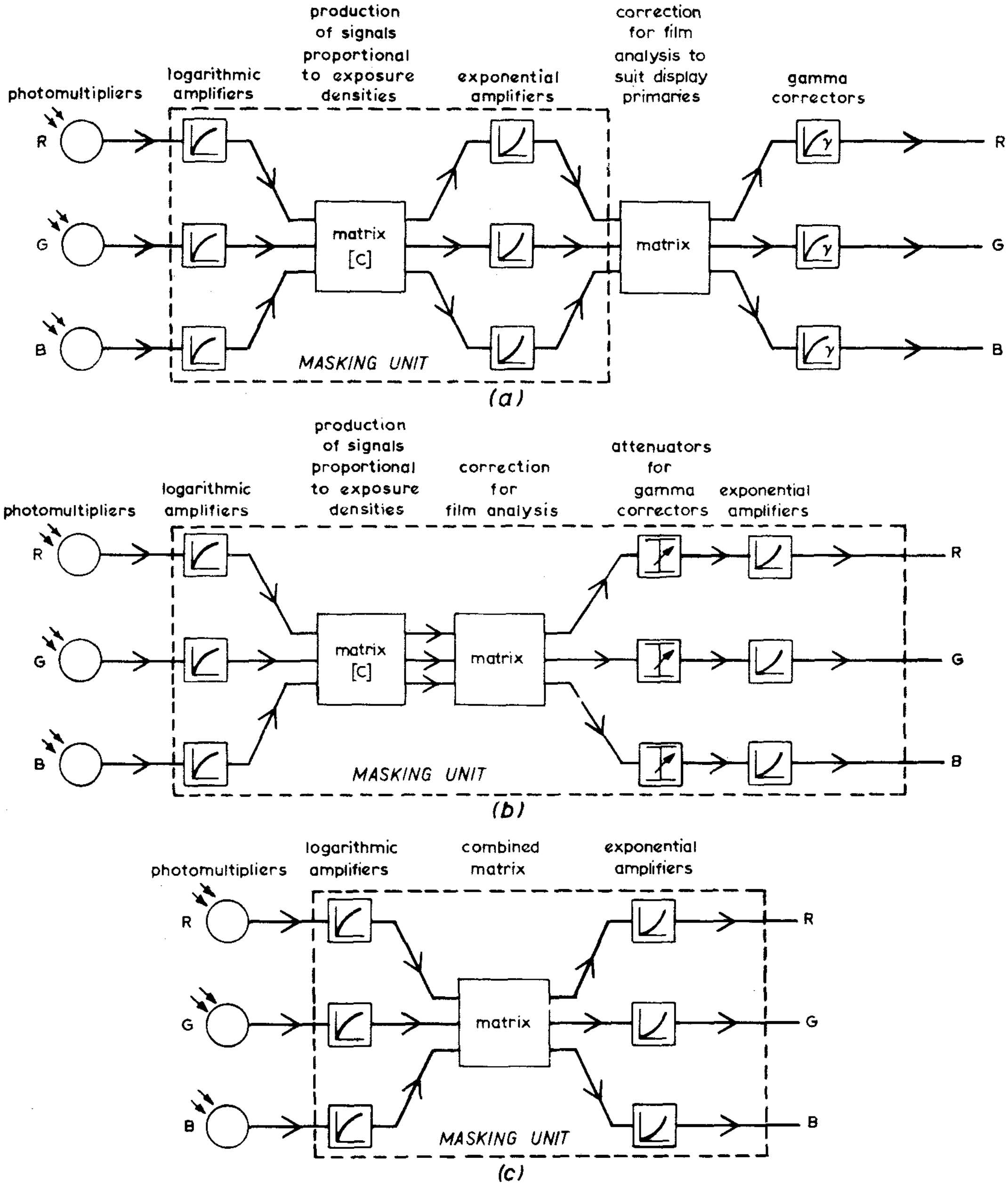

Fig. 5 - The two means envisaged of incorporating correction for film analysis

(*a*) Correction carried out on linear signals (*b*) Correction carried out on logarithmic signals
(*c*) Simplified circuit equivalent to (*b*)

The circuit of Fig. 5(*a*) includes three non-linear devices in each of the three channels: a logarithmic amplifier, an exponential amplifier and a gamma corrector. For ease of instrumentation it is desirable to reduce the number of non-linear devices to a minimum. Were it not for the second matrix, the gamma corrector in each channel could be replaced by an attenuator preceding the exponential amplifier or by appropriately modifying** the matrix [C] of the masking unit. The question therefore arises as to whether a satisfactory partial corrector for the unsuitable film analysis, which ought ideally to be performed on linear signals, could be performed either on logarithmic signals or on gamma-corrected signals. Either of these approximate approaches would remove the need for a matrix between the exponential amplifiers and the gamma correctors, and enable the latter to be eliminated.

Now Hanson and Brewer[7] have found that if analysis according to colour-mixture curves is required but real film sensitivities are used it is possible to achieve a partial correction by photographic masking. Moreover, the mask necessary for this purpose can be calculated independently of that required to offset deficiencies in the dye characteristics. Since electronic and photographic masking are directly analogous, therefore, it would appear possible to build a correction for film analysis into the electronic masking unit. This possibility is also examined in Section 3.2 and it is found that correction carried out in this way is almost as effective as that obtained by operating on 'linear' signals. Fig. 5(*b*) shows a circuit in which this is done, and Fig. 5(*c*) shows the simplification resulting from such a procedure.

Note that if a telerecording system can be designed in such a way that the red, green and blue television signals are made to control the exposures made on the red, green and blue sensitive layers respectively of a colour film, all that the telecine machine is required to do during replay is to produce signals proportional to these three exposures. Thus it is desirable to use electronic masking, but subsequent correction for the film taking sensitivities is not required.

3. CALCULATION OF OPTIMUM PARAMETERS

The foregoing discussion has indicated that the process of electronic masking may be analysed in terms of the three steps (see Fig. 3(*b*)), each of which may be considered independently:

(a) An appropriate scanner analysis followed by a set of logarithmic amplifiers and a matrix ($[B]^{-1}$) in order to derive signals proportional to the densities c, m and y of the three print dyes.

(b) A further matrix ($[A]^{-1}$) to undo the effects of interimaging and photographic masking, and gain controls to correct gamma, in order to give signals proportional to the original exposure densities, D_r, D_g and D_b.

(c) Further correction to reduce errors that are caused by the unsuitability of the film taking sensitivities to a display using NTSC primaries (or any other set of additive primaries).

The matrix operations described in the above three steps could be achieved by the use of only one matrix, as shown in Fig. 5(*c*). Nevertheless the calculations are appreciably simplified if they are considered separately in the first place.

Interimaging is a complicated process caused, for example, when the development of one layer of a tri-pack film is influenced by the development taking place in adjacent layers. It is not the purpose of this report, however, to consider in detail the mechanism by which interimaging, or indeed photographic masking, causes each print dye to be a function of all three exposures. The overall effect of such processes is claimed to be negligible for certain types of film (including the one featured in the calculations to be given) but can be appreciable for others. Quantitative information is not usually available, but it would be sufficient for our purpose to calculate an approximate linear matrix connecting the exposure densities D_r, D_g and D_b (which can be calculated given the spectral sensitivities of the film) and the print dye densities c, m and y (established by measurement) relating to a number of test colours whose spectral composition is known[5]. The inverse of this matrix would be used in carrying out step (b) above. The following two sections will describe calculations made to establish values for the parameters concerned in implementing steps (a) and (c).

Note that the calculations whose description follows have all assumed that signals suited to the NTSC primaries are required. If the appropriate numerical changes are applied however, the method is equally adaptable to any other set of display primaries.

3.1. Scanner Analysis and Masking Requirements to give Signals Proportional to Print Dye Densities

Section 2.3 has indicated that in specifying scanner analysis characteristics for use with electronic masking one needs to strike a balance between the conflicting requirements of accurate colorimetry and good signal-to-noise ratio. Fig. 6 enables this conflict to be examined further. It shows the spectral density characteristics of the yellow (curve (*a*)), magenta (curve (*b*)) and cyan (curve (*c*)) dyes used in a typical positive print stock. (The densities shown relate to a neutral with respect to Illuminant C.)

** Mathematically the procedure is equivated to multiplying a $[3 \times 3]$ matrix by the scalar $1/\gamma$, where γ is the gamma of the display tube.

If noise did not need to be considered, it follows from Section 2.2 that one could choose any three different wavelengths for monochromatic analysis, and the appropriate masking would then enable a completely accurate measure of the three dye densities to be obtained. If a minimum amount of masking correction were desirable one would choose the three wavelengths where a minimum overlap of dye characteristics occurred - in this case at around 440 nm, 530 nm and 660 nm.

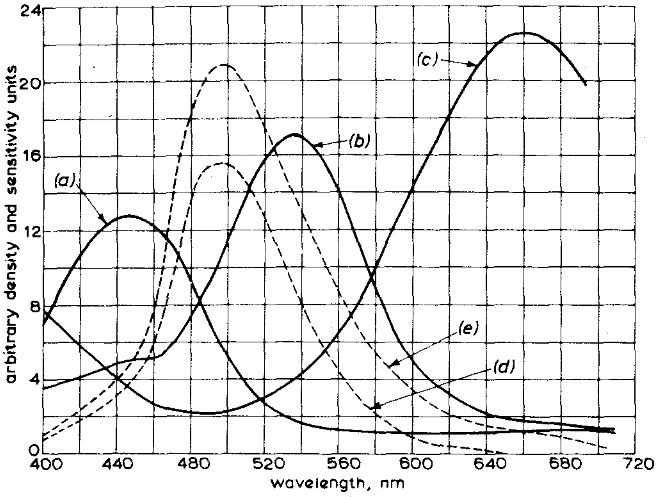

Fig. 6 - Film and scanner characteristics used in calculation

(*a*) Spectral density of yellow dye
(*b*) Spectral density of magenta dye
(*c*) Spectral density of cyan dye
(*d*) Product of emission of crt and sensitivity of photomultiplier used in blue and green channels
(*e*) Product of emission of crt and sensitivity of photomultiplier used in red channel

Also shown in Fig. 6, however, at (*d*) and (*e*) are the products of the spectral emission of the cathode-ray tube (crt) and the spectral sensitivities of the two photomultiplier tubes used in a typical flying-spot colour scanner. These two curves suggest that for maximum signal-to-noise ratio, the three analysis characteristics should be made as broad as possible and clustered as closely as possible within the region 480 to 530 nm. Two complications arise, however. The first has already been mentioned; as the analysis is broadened the masking becomes inexact, and colorimetric errors are accumulated. The second is that if the three analyses are moved away from the 440 nm, 530 nm and 660 nm regions towards the peak sensitivity region, the signals obtained from the photomultipliers are greater, and therefore have better signal-to-noise ratios, but an increased masking correction is required, and therefore the reduction of signal-to-noise ratio incurred within the masking circuits is increased. It follows that when the scanner analysis together with the elements of the matrix have been optimized it will not be possible to improve the colorimetry further without more than counterbalancing the improvement by an increase in noise. If on the other hand a small adjustment is made to the scanner analysis so as to improve the signal-to-noise ratio at the outputs of one or more of the photomultipliers then the improvement will be more than counterbalanced by the worsening of the colorimetry. It might be possible to restore the original degree of colour accuracy by adjusting the elements of the matrix*, but this procedure would then be found to make the signal-to-noise ratio worse than it had been originally. How these conditions may be satisfied simultaneously depends on the characteristics of the particular film and scanner considered. Although only one type of film and one particular scanner were considered in the calculations to be described, it is believed that the conclusions reached are substantially valid for a wide variety of films and scanners.

Matrix $[B]^{-1}$ may be considered to apply signals that correct for the overlaps in the dye spectral density characteristics. Since it is chiefly in plain areas of the picture that colour errors are noticeable, it is usually acceptable to limit the bandwidth of these correction signals. If this is done, the impairment of signal-to-noise ratio produced by the masking circuit is reduced. Both 'wide-band' and 'band-limited' masking (illustrated in Fig. 7) were considered in the analysis to be described.

Whilst the scanner analysis was being optimized, it was assumed that all other steps in the film-television process were carried out with complete accuracy. It was assumed for instance that the film analysis was ideally suited to the NTSC primaries, and that any interimaging etc. could be completely compensated.

3.1.1. Choice of Test Colours and Method of Assessing Colour Accuracy

It was first necessary to select a number of test colours which could be used to assess the colorimetric accuracy of the masking process. The simplest way of doing this was to choose a representative number of dye density sets, and then to calculate the colours that each would represent. Thus if a given set comprised densities c, m and y, then assuming no interimaging and no photographic masking within the film process and assuming a gamma of unity, these values would be equal to the exposure densities D_r, D_g and D_b. The original exposures are therefore given by equation (1) as

$$R = 10^{-c},\ G = 10^{-m},\ B = 10^{-y}$$

Assuming then that the original film analysis is ideally suited to NTSC primaries, the appropriate matrix enables the chromaticity and luminance corresponding to R, G and B to be deduced. Table 1 lists the dye density sets used in the calculations, together with the exposure values and the chromaticities and luminances of the corresponding colours. Dye density combination No. 1 was intended to represent a white, and so exposures and luminances are expressed as fractions of those relating to No. 1. Nos. 14, 15 and 16 represent three neutral colours. The other combinations were chosen from the range of dye densities of chief interest, and represent colours having reasonably high luminances and various chromaticities within the gamut of the NTSC primaries. It was thought that if the system were capable of handling high luminance colours and neutral colours, then it would satisfactorily reproduce low luminance colours. Fig. 8 shows the above test colours plotted on a C.I.E. - U.C.S. diagram.

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* The fact that this compensation may be made in several ways helps to explain the difficulties that accompanied the optimization procedure. See Section 3.1.3.

These are not, of course, the colours appearing on the film print. The spectral transmission of the print corresponding to each of the above dye density combinations was obtained as

$$T(\lambda) = 10^{-D(\lambda)}$$

where $D(\lambda)$ is the spectral density of the print given as

$$D(\lambda) = cD_1(\lambda) + mD_2(\lambda) + yD_3(\lambda),$$

$D_1(\lambda)$, $D_2(\lambda)$ and $D_3(\lambda)$ being the spectral densities of e.n.d. = 1 amounts of the cyan, magenta and yellow dyes respectively.

The above spectral transmission characteristic $T(\lambda)$ is analyzed by the film scanner, and the object of the masking procedure is then to obtain signals c^1, m^1 and y^1 that are as close as possible to c, m and y throughout the colour gamut. In carrying out the optimization, however, the important consideration was not the differences between densities c, m and y and signals c^1, m^1 and y^1, but the differences between the colours that the two sets represent. These colour differences were therefore expressed in terms of just noticeable differences (jnd) and used in conjunction with a factor expressing noise performance to assess the proposed scanner analysis characteristics.

The mean colorimetric error was defined as

$$n = \left[\bar{n}_c^{\,2} + \bar{n}_L^{\,2}\right]^{1/2}$$

where $\bar{n}_c$ was the mean chromaticity error and $\bar{n}_L$ was the mean luminance error. For each colour,

$$n_c = \left[(u - u_0)^2 + (v - v_0)^2\right]^{1/2} / .00384$$

where (u_0, v_0) and (u, v) were the original and reproduced chromaticities expressed with respect to the 1960 C.I.E. uniform chromaticity scale diagram, and

$$n_L = |\log_e L - \log_e L_0| / .0198$$

where L_0 and L were the original and reproduced luminances, expressed relative to white.

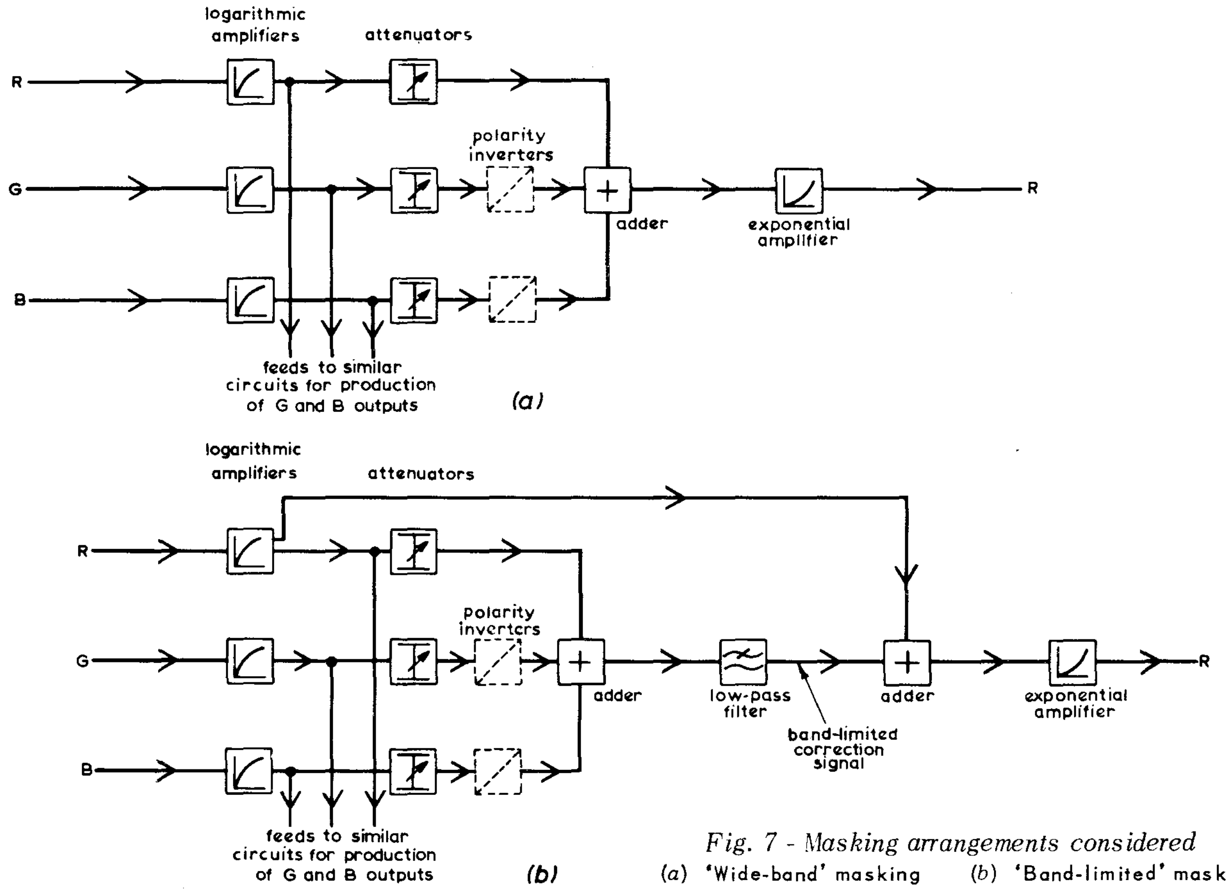

Fig. 7 - Masking arrangements considered
(*a*) 'Wide-band' masking (*b*) 'Band-limited' masking

TABLE 1

dye densities, e.n.d.				exposures			colour		
No.	*c*	*m*	*y*	*R*	*G*	*B*	*u*	*v*	*L*
1	0.3	0.3	0.3	1.000	1.000	1.000	0.201	0.307	1.000
2	0.9	0.4	0.4	0.251	0.794	0.794	0.141	0.297	0.632
3	0.4	0.9	0.4	0.794	0.251	0.794	0.260	0.271	0.476
4	0.4	0.4	0.9	0.794	0.794	0.251	0.212	0.347	0.732
5	1.6	0.6	0.6	0.050	0.501	0.501	0.116	0.293	0.366
6	0.6	1.6	0.6	0.501	0.050	0.501	0.293	0.251	0.236
7	0.6	0.6	1.6	0.501	0.501	0.050	0.217	0.364	0.450
8	0.9	0.9	0.4	0.251	0.251	0.794	0.183	0.242	0.313
9	0.4	0.9	0.9	0.794	0.251	0.251	0.300	0.324	0.414
10	0.9	0.4	0.9	0.251	0.794	0.251	0.138	0.346	0.570
11	1.6	1.6	0.6	0.050	0.050	0.501	0.166	0.182	0.102
12	0.6	1.6	1.6	0.501	0.050	0.050	0.394	0.339	0.185
13	1.6	0.6	1.6	0.050	0.501	0.050	0.100	0.369	0.315
14	0.6	0.6	0.6	0.501	0.501	0.501	0.201	0.307	0.501
15	1.0	1.0	1.0	0.200	0.200	0.200	0.201	0.307	0.200
16	1.3	1.3	1.3	0.100	0.100	0.100	0.201	0.307	0.100

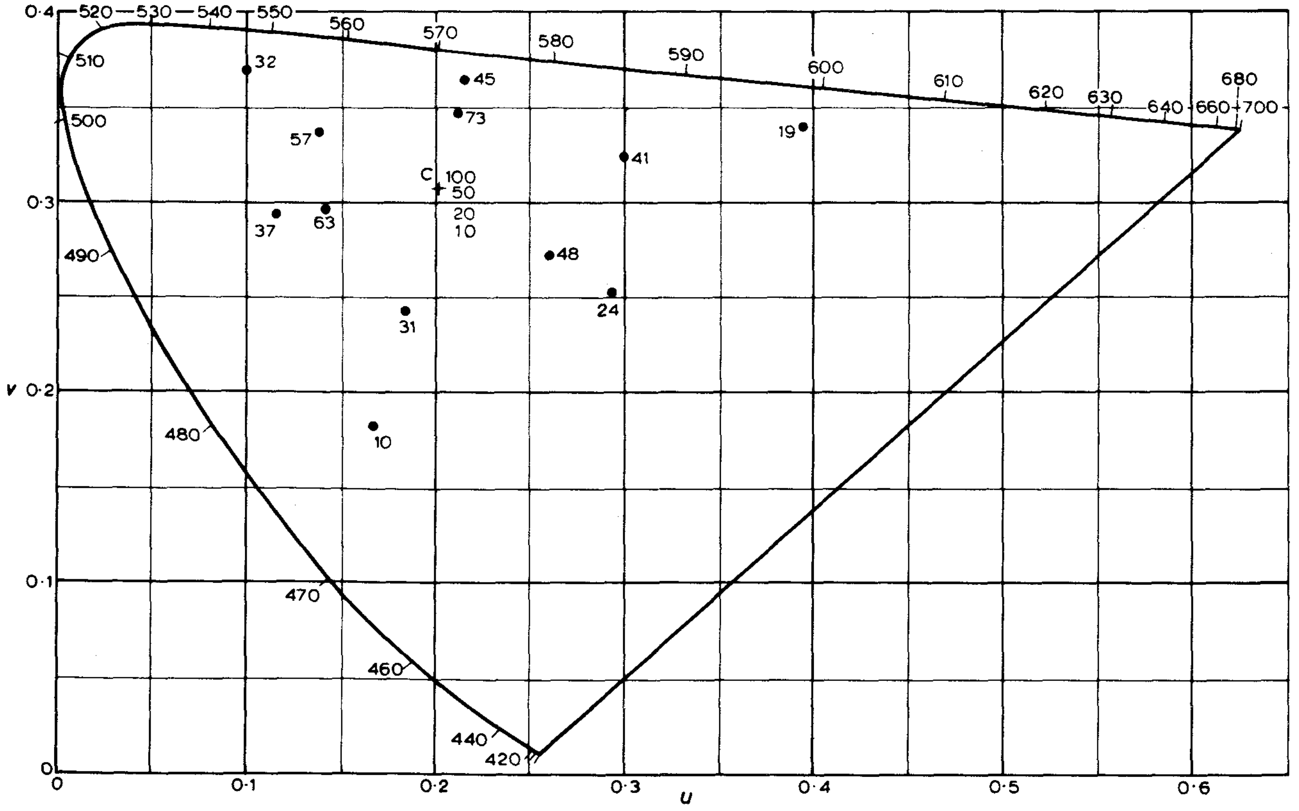

Fig. 8 - Colours which the dye density combinations used in the calculations represent
Figures are relative luminances expressed as percentages

3.1.2. Method of Assessing Noise Performance

Suppose that the noise signals associated with the normalized scanner signals E_r, E_g and E_b are δE_r, δE_g and δE_b. Then matrix $\begin{bmatrix}B\end{bmatrix}^{-1}$ is made to operate on

$$\log(E_r+\delta E_r)$$

etc.

$$= \log E_r + \log(1+\delta E_r/E_r)$$

etc.

now since for an acceptable scanner δE_r is much less than E_r, we may expand the above expressions as

$$\log E_r + h.\delta E_r/E_r \qquad \text{where } h = \log_e 10$$

etc. $\qquad\qquad\qquad\qquad \approx 2{\cdot}3026$

At the output of the matrix, therefore, we have

$$\begin{bmatrix}B\end{bmatrix}^{-1}\begin{bmatrix}\log E_r\\ \log E_g\\ \log E_b\end{bmatrix} + \begin{bmatrix}B\end{bmatrix}^{-1}\begin{bmatrix}h\delta E_r/E_r\\ h\delta E_g/E_g\\ h\delta E_b/E_b\end{bmatrix} \qquad (8)$$

if R, G and B are the required output signals and δR, δG, and δB are the noise signals that accompany them, the above expression must be equal to

$$\begin{bmatrix}\log(R+\delta R)\\ \log(G+\delta G)\\ \log(B+\delta B)\end{bmatrix}$$

which by an argument similar to that used above may be expanded as

$$\begin{bmatrix}\log R\\ \log G\\ \log B\end{bmatrix} + \begin{bmatrix}h\delta R/R\\ h\delta G/G\\ h\delta B/B\end{bmatrix} \qquad (9)$$

The first terms in expressions (8) and (9) relate to the wanted signal components, and they are therefore equivalent, as equation (6) shows. The required noise relationship is therefore given by

$$\begin{bmatrix}\delta R/R\\ \delta G/G\\ \delta B/B\end{bmatrix} = \begin{bmatrix}B\end{bmatrix}^{-1}\begin{bmatrix}\delta E_r/E_r\\ \delta E_g/E_g\\ \delta E_b/E_b\end{bmatrix}$$

so that if B^{-1} is equal to

$$\begin{bmatrix}b_{11} & b_{12} & b_{13}\\ b_{21} & b_{22} & b_{23}\\ b_{31} & b_{32} & b_{33}\end{bmatrix}$$

we have

$$\delta R = b_{11}(\delta E_r/E_r)R + b_{12}(\delta E_g/E_g)R + b_{13}(\delta E_b/E_b)R$$

and similar expressions for δG and δB. In a good flying-spot scanner the noise originates mainly in the photomultiplier tubes and is proportional to the square root of the signal current. Thus δE_r is proportional to $\surd(k_r.E_r)$ where k_r is the factor which multiplied the red analysis characteristic to normalize it so that $E_r = 1$ volt for white. Similarly δE_g is proportional to $\surd(k_g.E_g)$ and δE_b to $\surd(K_b.E_b)$. Therefore δR above is proportional to

$$b_{11}\surd(k_r/E_r).R + b_{12}\surd(k_g/E_g).R + b_{13}\surd(k_b/E_b).R$$

and similar expressions may be written for δG and δB.

These noise components δR, δB and δG cause both the chromaticity and the luminance of the reproduced colour to be perturbed; and their relative influence on the observed disturbance is dependent on the mean chromaticity. Hacking[8] has calculated various weighting coefficients for flying-spot scanners which apply when the chromaticity fluctuations are just visible, and those coefficients $l{:}m{:}n$ were used in the present analysis.

If 'wide-band' masking is used (Fig. 7), the noise present at each of the matrix outputs has components contributed by each of the primary sources. Therefore when the total effect of the noise is assessed using the above weighting coefficients, some components will be coherent and therefore their amplitudes will add, whilst some will be incoherent and therefore their powers will add. Bearing this in mind, the total observed noise associated with a particular colour is proportional to

$$\Big[(k_r/E_r)\,(b_{11}\,l\,R + b_{21}\,m\,G + b_{31}\,n\,B)^2 + (k_g/E_g)\,(b_{12}\,l\,R + b_{22}\,m\,G + b_{32}\,n\,B)^2 + (k_b/E_b)\,(a_{13}\,l\,R + a_{23}\,m\,G + a_{33}\,n\,B)^2\Big]^{1/2} \qquad (10)$$

If, however, 'band-limited' masking is used, the correction signals may for simplicity be taken to be noiseless. The expression for noise then becomes

$$\Big[(k_r/E_r)\,l^2R^2 + (k_g/E_g)\,m^2G^2 + (k_b/E_b)\,n^2B^2\Big]^{1/2} \qquad (11)$$

Noise levels N_W, N_R, N_G and N_B were calculated using the above expressions for four of the test colours (Nos. 1, 12, 13 and 11 - white, red, green and blue) the appropriate weighting factors being taken from Fig. 9 of reference 5. In addition a composite noise value N_{rss} was calculated as the root-sum-square of the above four figures.

The noise performance of a typical flying-spot colour scanner had been measured. Calculations were therefore made to establish the optimum masking for this scanner (Section 3.1.3.). This data enabled the above figures N_W, N_R, etc. to be converted to absolute signal-to-noise ratios.

Since a compromise was to be made between colour accuracy and noise performance it was necessary to express N_{rss} and n in the same units and then to derive from them an overall impairment figure used to control the optimization procedure.

To do this a value of signal-to-noise ratio at which the noise would just become visible was specified. The difference between the actual signal-to-noise ratio and this threshold value was then converted to just noticeable difference units by using a relationship established by Geddes[9]. This suggested that a 1 jnd* difference in impairment would be caused by a change of 5 dB in signal-to-noise ratio.

Finally, the overall impairment figure was obtained as the root sum of squares of the noise impairment figure (jnd) and the colour error n.

The noise threshold level was not easy to estimate because it had to be borne in mind that noise would be accentuated by the additional processing necessary to correct for the film analysis. Similarly whilst assessing colour accuracy one had to remember that errors probably greater than those at present being considered would be produced at other points in the film-television chain. It was difficult therefore to decide how much relative weight should be attached to colour error and noise when determining an overall impairment figure. It was somewhat arbitrarily decided that a particular flying-spot scanner at Research Department had a just satisfactory noise performance when used for masking, but that its colorimetry should be improved. The noise level of this scanner was therefore chosen for the threshold, and colour errors incurred at other parts of the film-television chain were at present ignored.

3.1.3. The Calculation

It was at first thought that the optimum analysis and mask could be derived without difficulty by making use of the Elliott computer library programme for system optimization which had been used to find the optimum analysis and linear matrix for scanners not employing masking[2]. A full description of this method is given in reference 2, but briefly the technique was to feed to the computer expressions enabling the overall impairment figure to be derived from the values of a series of parameters chosen to define the system. In the present instance these parameters comprised the wavelengths at which the peaks of the optical transmission characteristics* were to occur, the wavelengths on either side of each peak at which the characteristics would indicate 50% of the peak transmission, and the quantities b_{11} to b_{33} that defined the mask – 18 parameters in all. The transmission characteristics were constructed as before[2] by making use of a particular curve shape that was considered typical of what could be achieved in practice. The object of the programme was to determine by a series of approximations the parameter values that would produce the minimum overall impairment. Unfortunately it was found that the values reached by the 18 parameters were always very close to the values ascribed to them at the start of the calculation, regardless of what these starting values might be. Such a result is not altogether surprising where a large number of parameters are being optimized. The process of optimization amounts to the exploration of a multi-dimensional surface to find the lowest point. The more complicated this surface, the more likely it is to contain several minima. The lowest value reached by the programme is then likely to be that of the minimum that happens to be nearest to the starting point chosen.

The optimization programme could therefore only be relied upon to make small final adjustments to the parameters after they had already been adjusted to be near the optimum.

In order to determine the optimum region a survey was made of 8000 different scanner analysis characteristics. These were produced by combining in all possible ways a 'red' transmission characteristic curve shape chosen from four possibilities, - a 'green' curve chosen from four possibilities, and a 'blue' curve similarly chosen. The peaks of each of the three curves could be positioned at any one of five different wavelengths.

Fig. 9 shows the twelve curves used in the calculations and indicates the peak positions investigated.

The transmission curves were made to peak at 70% (red), 50% (green) and 55% (blue) because these were the peak transmissions of the Research Department scanner. These levels are also typical of what can frequently be achieved in practice, and the use of them therefore enables a fairly realistic estimation of noise performance to be made. An error in the data prevented green curve 2 from being symmetrical but this did not seriously affect the survey, for there was no reason to suppose that a set of symmetrical curves would finally be required.

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* Geddes' curve showing 'mean subjective grade' as a function of the ratio of 625-line picture signal to rms noise, having a spectrum independent of video frequency, gives (by extrapolation) a value of 44 dB for 'just imperceptible' and 39 dB for 'just perceptible' - a 'just noticeable difference' corresponding to a change of 5 dB.

* The characteristics of the dichroic and other filters inserted into the optical path of the scanner in order to divide the light produced by the cathode-ray tube between the three photomultipliers.

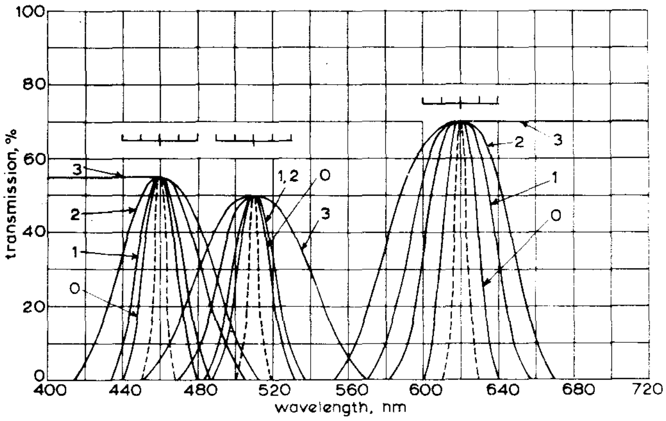

Fig. 9 - Optical transmission characteristics tested

—— curves used in compiling set of 8000

------ narrow band curves separately considered

⊥ wavelengths assumed for peaks of curves

The signals obtained by analysis of the test colours according to each of the 8000 combinations were calculated. A matrix was then determined for each combination by applying the method of least squares[10] to the solution of a set of equations of the form defined earlier by equation (5). The corresponding noise figures were also calculated as described in Section 3.1.2. The 8000 sets of results were scrutinized carefully, and data appropriate to the best one was used to determine starting values for the optimization programme. Thus the optimum solution was obtained. The calculations were made twice over, once for 'wide-band' masking, and once for 'band-limited' masking (Fig. 7).

Also shown in Fig. 9 are narrow-band transmission curves used at all possible combinations of peak wavelengths in a separate calculation to establish the optimum positions for a set of almost monochromatic analyses.

3.1.4. Results

As expected, narrow-band analyses together with the appropriate masking always gave excellent colorimetry, but with poor noise performance. Narrow analysis required minimum masking when the curves were positioned near to the peaks of the dye density curves (Fig. 6) where minimum overlapping occurred. The noise performance was improved however, if the narrow analysis curves were moved away from these positions towards the peaks (approx. 498 mm) of the characteristics shown in Fig. 6(*d*) and (*e*). The amount of such adjustment necessary for optimum noise performance depended on the method of masking correction. For 'wide-band' masking (Fig. 7(*a*)), the optimum positions were at 637 nm (red), 525 nm (green) and 468 nm (blue). If, however, 'band-limited' masking (Fig. 7(*b*)) was envisaged, the noise performance was not only better whatever the analysis positions, but also continued to improve as the curves were moved much nearer to 498 nm.

As the analysis characteristics were broadened, similar improvements in signal-to-noise ratio could be obtained by moving the characteristics away from the dye absorption peaks towards 498 nm. The correction obtained by masking became less precise, however, as the analysis characteristics were broadened, and colour errors were produced. These errors need not be very great, but they were at a minimum when a minimum degree of masking was required, that is, when the curves were positioned near to the dye absorption peaks.

In general, broadening the analysis curves at first improves the noise performance at some small loss to colour accuracy, but eventually the colour rapidly deteriorates whilst the benefit to noise performance is greatly reduced. None the less, and because of the broad-band nature of the dye characteristics, very accurate measures of dye density can be achieved using the appropriate masking for a very wide range of analysis curves. A corollary to this fact is that a set of analysis curves chosen to give optimum masking for a particular type of film is likely to be very suitable for any other type provided that the masking equation is altered appropriately.

'Band-limited' masking was found to have a decided noise advantage as compared with 'wide-band' masking, particularly in regions of saturated colour. The advantage was much reduced in white areas however, where some noise cancellation occurred when the weighting factors l, m and n were applied (see equations (10) and (11)). This was because noise components introduced into each signal channel by masking were coherent and in antiphase with the major noise components within the channels from which they were derived. Thus although 'band-limited' masking is always superior to 'wide-band' masking, the advantage actually obtained depends on the colour considered and also on the masking equation.

The optimum curves obtained for 'wide-band' and for 'band-limited' respectively were very similar indeed, and results relating to 'band-limited' masking will therefore be chosen.

Fig. 10 shows the overall optimum analysis curves. It also repeats curves shown in Fig. 6, since these were the major constraints in the optimization procedure. These analysis characteristics result from the use of optical transmission characteristics* defined according to Table 2.

* See note on page 13, col. 2.

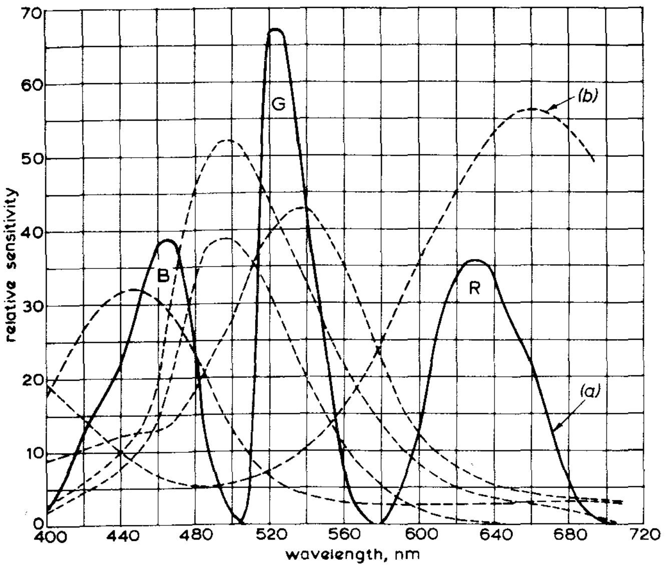

Fig. 10 - Optimum scanner analysis characteristics for masking
(*a*) Optimum characteristics
(*b*) Curves repeated from Fig. 5

TABLE 2

		nm
Red Transmission	Peak	644
	50% points	610, 680
Green Transmission	Peak	525
	50% points	516, 555
Blue Transmission	Peak	438
	50% points	403, 472

The corresponding masking equation is given by

$$\begin{bmatrix} c \\ m \\ y \end{bmatrix} = \begin{bmatrix} 1{\cdot}18 & -0{\cdot}17 & -0{\cdot}10 \\ -0{\cdot}19 & 1{\cdot}35 & -0{\cdot}23 \\ -0{\cdot}24 & -0{\cdot}62 & 1{\cdot}93 \end{bmatrix} \begin{bmatrix} \log E_r \\ \log E_g \\ \log E_b \end{bmatrix}$$

where the [3 x 3] matrix is $[B]^{-1}$ (See equation (5) and Fig. 3(*b*)).

On the basis of the assumptions made, the above analysis gives signal-to-noise ratios of 40 dB (white), 40 dB (red), 41 dB (green) and 46 dB (blue). Bearing in mind the triangular nature of the noise spectrum these figures indicate that noise would be hardly perceptible. The colour error figure is 0·2 jnd, which means that errors introduced by measurement of the dye densities are negligible as compared with errors occurring at other points in the process.

3.2. Correction for Film Analysis

The determination of an optimum linear matrix to correct for the film taking sensitivities followed a method described earlier.[11] A series of 23 test colours was chosen to represent the range of colours normally encountered. Sensitivity curves were obtained for the colour film whose dye characteristics had featured in the masking calculation. The signals *R*, *G* and *B* that would be produced by a device having these curves as analysis characteristics and exposed to the test colours by Illuminant 3000°K were then calculated. A linear matrix was then optimized so that when applied to these signals it would produce a further set R_T, G_T and B_T which, controlling a set of NTSC primaries balanced to Illuminant C, would produce colours matching as closely as possible the original test colours viewed by Illuminant C. It was found that if no matrix were used, the colour errors would be of the order of 13·7 jnd, but that this could be reduced to 6·4 jnd by the use of the following matrix

$$\begin{bmatrix} R_T \\ G_T \\ B_T \end{bmatrix} = \begin{bmatrix} 0{\cdot}61 & 0{\cdot}41 & -0{\cdot}02 \\ -0{\cdot}05 & 1{\cdot}09 & -0{\cdot}04 \\ 0 & -0{\cdot}06 & 1{\cdot}06 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

A second optimization was carried out, assuming that the matrix was required to operate on logarithmic rather than linear signals. By this means the error was reduced to 6·5 jnd, the corresponding matrix being

$$\begin{bmatrix} \log R_T \\ \log G_T \\ \log B_T \end{bmatrix} = \begin{bmatrix} 0{\cdot}80 & 0{\cdot}23 & -0{\cdot}03 \\ -0{\cdot}16 & 1{\cdot}19 & -0{\cdot}03 \\ -0{\cdot}08 & 0{\cdot}16 & 0{\cdot}92 \end{bmatrix} \begin{bmatrix} \log R \\ \log G \\ \log B \end{bmatrix}$$

These residual errors are quite large when compared with what a colour television camera can achieve[2], but this is because the original film analysis departs substantially from colour-mixture curves, and so a precise correction for a wide range of colours is not possible. None the less these errors are smaller than the overall errors that would have been incurred if the scanner analysis were designed to reproduce the film as it would have appeared in an optical projection.

The calculations were repeated for a different set of film sensitivities, and similar results were obtained; an error of 11·9 jnd was reduced to 5·4 jnd by a matrix operating on linear signals and to 6·3 jnd by a matrix operating on logarithmic signals.

If correction were confined to logarithmic signals, therefore, the complete process of film correction would be given by

$$\begin{bmatrix} \log R_T \\ \log G_T \\ \log B_T \end{bmatrix} = \begin{bmatrix} 0{\cdot}80 & 0{\cdot}23 & -0{\cdot}03 \\ -0{\cdot}16 & 1{\cdot}19 & -0{\cdot}03 \\ -0{\cdot}08 & 0{\cdot}16 & 0{\cdot}92 \end{bmatrix} \begin{bmatrix} \\ A \\ \\ \end{bmatrix}^{-1} \begin{bmatrix} 1{\cdot}18 & -0{\cdot}17 & -0{\cdot}10 \\ -0{\cdot}19 & 1{\cdot}35 & -0{\cdot}23 \\ -0{\cdot}24 & -0{\cdot}62 & 1{\cdot}93 \end{bmatrix} \begin{bmatrix} \log E_r \\ \log E_g \\ \log E_B \end{bmatrix}$$

where matrix $[A]^{-1}$ takes account of interimaging, photographic masking and gamma correction. (In the case investigated the overall effect of interimaging and photographic masking is claimed to be negligible, and $[A]^{-1}$ therefore becomes a scalar multiplying factor). The third matrix on the right-hand side, $[B]^{-1}$, takes account of the negative-to-positive print process, while the first matrix on the right-hand side applies correction for the film taking sensitivities.

The chief errors incurred in the complete process are likely to be those associated with the correction for film analysis. Fig. 11 shows the errors remaining when a matrix operating on logarithmic signals is used, and relates to the set of colours used in producing Figs. 1 and 2. Comparison of these three figures will show that compatibility between television cameras and film scanners is likely to be greatly improved if electronic masking is used.

4. CONCLUSIONS

The electronic masking process may be regarded as composed of three parts: (i) use of the scanner analysis together with correction applied to logarithmic signals to obtain measurements of the film dye layer densities, (ii) further processing applied to logarithmic signals to derive a measure of the original exposure densities, and (iii) correction then applied to either linear or logarithmic signals to improve compatibility between the film taking sensitivities and those appropriate to the television display primaries. The first and third of these steps have been examined in detail; the second has been discussed qualitatively.

A set of optimum scanner analysis characteristics for masking has been derived by combining considerations of colorimetric accuracy and noise performance. It was found however that a very accurate measure of the dye densities may be

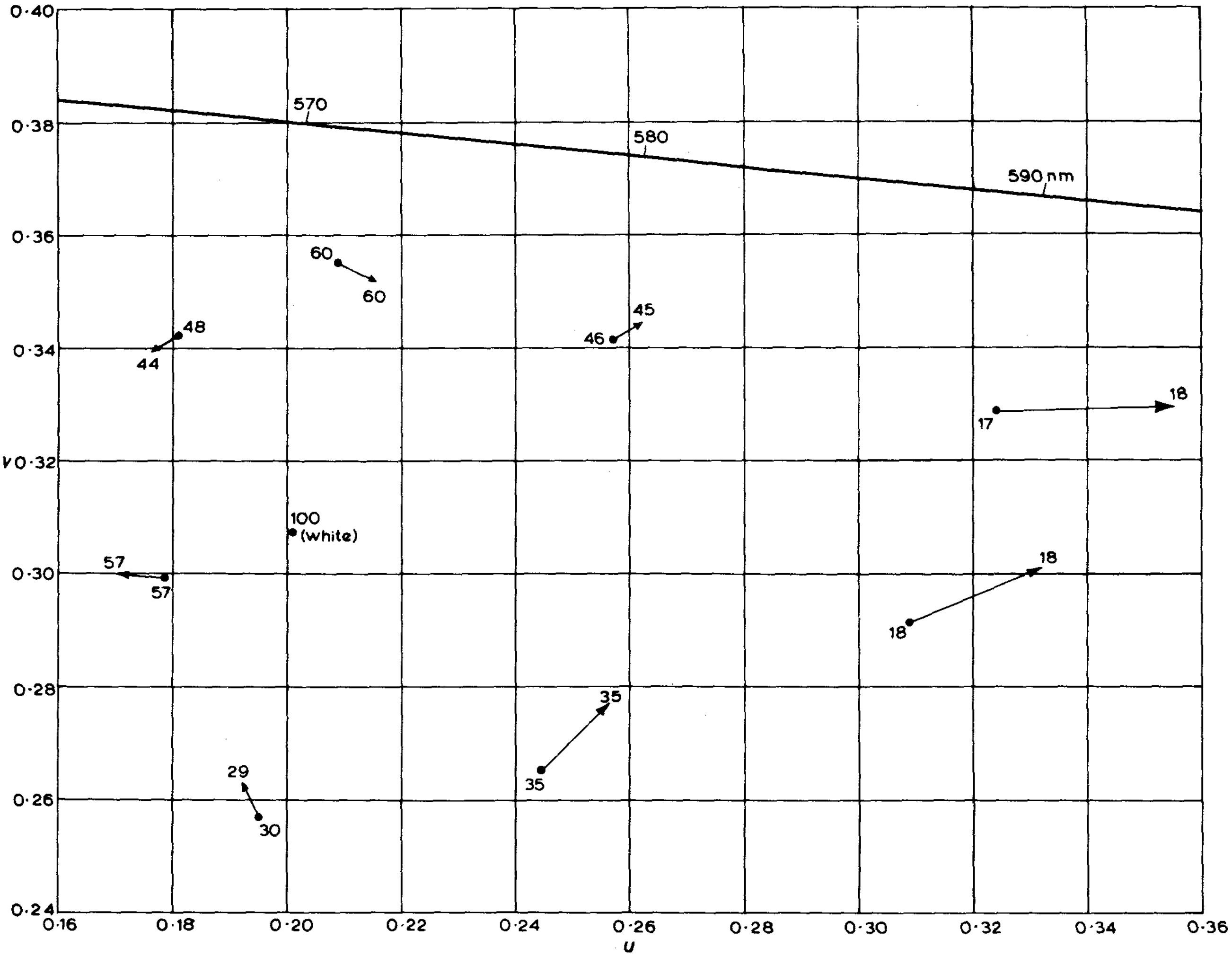

Fig. 11 - Calculated reproduction of a number of test colours analysed using typical film taking sensitivities, matrix operating on logarithmic signals, and NTSC primaries
Figures are relative luminances expressed as percentages
Reproduced colours at arrow heads

achieved using a wide range of scanner analysis characteristics provided that the masking unit is set up correctly.

Because the film taking sensitivities depart considerably from colour-mixture curves it is not possible by means of electronic correction to make them completely suitable for the television primaries. Some correction may be made, however, reducing colour errors to about 6 jnd.

Thus complete equality between colour pictures derived from film cameras and television cameras is not possible, but electronic masking enables a much closer agreement to be obtained than that resulting from an optical projection of the film print.

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